Nanoshearing

Collective carbon nanotube micromechanics

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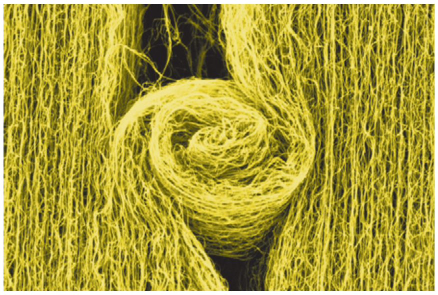
It has been hard to miss the buzz over the last 20 years surrounding one and two-dimensional carbon allotropes, e.g., carbon nanotubes (CNTs) and graphene. While most industrial applications utilizing these structures lie far in the future, interest remains in large part due to the confluence of properties found in this class of materials; there is not another that unites high electron mobility, tensile strength, compressibility, and thermal conductivity. However, one reason for many of these properties, the nanoscale sub-structure, is also one of the major difficulties facing their scalable implementation in new technologies. While much work has been directed toward nanoscale control of these materials, another direction has arisen for CNTs which bridges the size gap from nano to micro and up to films several millimeters in thickness. In order to do this, samples can be grown, for example, using a technique called chemical vapor deposition (CVD). The metal catalyst in CVD can be patterned or not, resulting in either islands or films of what are called vertically aligned carbon nanotubes (VACNTs) due to the way the tubes grow nominally perpendicularly to the supporting substrate. Being composed of individual CNTs, the resulting structures are hierarchical in nature: transverse isotropic on sufficiently large scales due to tube alignment, entangled and approaching isotropy on intermediate scales due to randomness during growth, and discrete at the smallest scales due to the individual CNT building blocks.

Recent studies suggest a wide range of applications for VACNTs, from low temperature, energy dissipating rubbers to thermo-mechanical components of microelectromechanical systems. Central to any application is a thorough understanding of the mechanical response of these foam-like structures. The first mechanical characterization of VACNTs, performed by Cao *et al.*[1], found that millimeter scale samples subject to uniaxial compression achieve high recoverability (< 20 % permanent deformation) even after thousands of compressive cycles to 85 % strain, with energy dissipated in each cycle. Deformation was observed to occur via the formation of sequential periodic buckles, i.e., localized strain as opposed to uniform collapse of the structure. Subsequent work has found that the viscoelastic response of VACNTs can match that of silicon rubber at room temperature while being invariant over a significantly wider range of temperatures than attainable for polymeric materials, –196 to 1000 °C[2]. Data characterizing both of these behaviors, sequential periodic buckling and exceptional energy dissipation, continues to accumulate. However, hypotheses describing these phenomena are currently limited by the lack of systematic study, in particular difficulties in characterizing VACNT's complex microstructure.



Our research focuses on the characterization of VACNTs under microcompression. At this size scale we can capture the collective behavior of the materials without sacrificing resolution of localized deformation events in the stress-strain response. The resulting complex, but informative data sets motivate understanding of the deformation mechanisms. In particular, we have performed compressions of 50 micron diameter pillars and various thicknesses of films while observing, *in situ*, the deformation behavior and simultaneously gathering stress-strain data[3,4]. These studies were performed using a custom-built, nano-mechanical module inside a scanning electron microscope we call SEMentor. In the pillar study, we found that the buckles accommodating deformation form via a local initiation event followed by propagation parallel to the growth substrate with each of these events corresponding to a local softening in the stress-strain response[3]. Using this structural response as inspiration, we proposed an elastic-viscoplastic constitutive relation that successfully captures sequential buckling and local softening events in an axisymmetric pillar model[5].

This month's cover image shows an SEM image of a structure formed at the vertical shear-off interface as a result of indentation into a VACNT film. A compressive force (via rectangular flat punch) was applied on the surface of the left-hand section of material (from bottom to top) while the right-hand portion remained stationary. As the left side was displaced upward, tubes at both interfaces wrapped around each other in order to accommodate the large deformation required of them at the interface. SEM observation of deformation gives researchers insight into the mechanical behavior, and specifically the strain accommodation mechanisms, of VACNTs.

Our research works toward a systematic characterization of the microstructural parameters that govern the mechanical response of VACNTs. We aim to provide a physics-based understanding of the deformation mechanisms, with one goal being a robust constitutive relation for VACNTs with the ability to guide both material and geometric design.

FURTHER READING

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3. Hutchens, S. B., *et al., Adv Func Mater* (2010) **20**, 2338.
4. Pathak, S., *et al., ACS Nano* (2012) doi: 10.1021/nm300376j.
5. Hutchens, S. B. *et al. J Mech Phys Sol* (2011) **59**, 2227.